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Signed on 29th day of August, 2005

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【Abstract】

1. Technical Field of the Invention As Claimed

The present invention relates to a broadband phase shifter using a coupled line and parallel open and short stubs.

2. Technical Objects of the Invention

The object of the present invention is to provide a broadband phase shifter having a new switching network structure by forming a coupled line, main transmission lines and parallel λ/8 open and short stubs on both ends of the main transmission lines in order to obtain broadband phase characteristic that the phase difference between two networks is uniform.

3. Summary of the Present Invention

The broadband phase shifter of the present invention includes a first path circuit network including a reference standard transmission line whose input/output characteristic impedance is Z_0 and electrical length is θ_1; a second path circuit network having two symmetrical main transmission lines connected to each other by a coupled line in the center and parallel open and short stubs connected to both ends of the two symmetrical main transmission lines, the main transmission lines having characteristic impedance Z_m and an electrical length θ_m and the parallel open and short stubs having characteristic

impedance Z_s and an electrical length θ_s; and a switching means for selecting only one path among the first path circuit network and the second path circuit network.

4. Major Usage of the Present Invention

The present invention is applied to a broadband phase shifter.

【Representative Figure】

Fig. 2

【Index】

broadband phase shifter, main transmission line, coupled line, parallel open/short stub, even mode and odd mode analysis, bandwidth

【Specification】

【Title of the Invention】

Broadband Phase Shifter Using a Coupled Line and Parallel Open/Short Stubs

【Brief Description of the Drawings】

Fig. 1 is a graph showing typical phase shifting characteristics between two standard transmission lines according to frequency.

Fig. 2 is a schematic diagram describing a network of a broadband phase shifter in accordance with the present invention.

Fig. 3 is an equivalent circuit showing a first path circuit network of the phase shifter circuit network of Fig. 2.

Fig. 4 is an equivalent circuit illustrating a second path circuit network of the phase shifter circuit network of Fig. 2.

Fig. 5 is a graph showing optimal Z_m and Z_s values by θ_m variations.

Fig. 6 is a graph illustrating an input/output VSWR and a phase bandwidth by θ_m variations.

Fig. 7 presents graphs showing optimal Z_m and Z_s.

Fig. 8 presents graphs showing input/output VSWR and phase bandwidth by R variations.

Fig. 9 presents frequency response characteristics of input/output return loss by R variations.

Fig. 10 shows graphs illustrating frequency response characteristics of phase error by R variations.

Fig. 11 is a diagram depicting a 180° phase shifter fabricated in accordance with an embodiment of the present invention.

Figs. 12 to 14 are graphs comparing simulated performances with measured ones in the 180° phase shifter whose θ_m value are 0°, 10°, and 90°, respectively.

Fig. 15 is a graph presenting simulated performances with measured ones in the 180° phase shifter with the standard Schiffman structure.

*Description on references for major parts in drawings

MTL: Reference main transmission line of a first path circuit network

TL1, TL2: transmission lines of a second path circuit network

CL1, CL2: Coupled lines of the second path circuit network

OSL1, OSL2: λ/8 (45°) parallel open stub line of the second path circuit network

SSL1, SSL2: λ/8 (45°) parallel short stub line of the second path circuit network

D1, D2: diodes selecting the first path

D3, D4: diodes selecting the second path

1, 2, 3, 4: Input Terminals

【Detailed Description of the Invention】

【Objects of the Invention】

【Field of the Invention and Related Prior Art】

The present invention relates to a broadband phase shifter using coupled lines and parallel open and short stubs; and, more particularly, to a broadband phase shifter having a structure of a transmission-type switching network which includes a coupled line, main transmission lines and parallel $\lambda/8$ (45°) open and short stubs formed on both ends of the main transmission lines in order to obtain broadband phase characteristic that the phase difference between two networks is uniform.

Generally, wireless communication systems, such as satellite communication, broadcasting, mobile communication and terrestrial communication, require various phased array antennas to be operated properly in a mobile environment. Electrical beams of the phased array antenna can be formed in a desired direction and a phase shifter is a key component of phased array antennas that is needed essentially to form the electrical beams.

The phase shifter is a device having two ports for changing the phase of radio frequency (RF) signals. It

provides a phase difference required by a control signal, i.e., direct current bias voltage/current, between input and output signals. Ever since a semiconductor diode phase shifter is developed in 1960s, phase shifters have been developed actively in response to the necessity for phased array technology.

Phase shifters are largely divided into a digital type and an analogue type. Digital type phase shifters are further divided into ones using ferrite materials and ones using semiconductor (diode or field-effect transistor (FET)) materials. The phase shifters using ferrite materials are suitable to high-power, small insertion loss, and high input/output match. The phase shifters using semiconductor materials are advantageous to obtain high switching rate, reciprocity, reliability, fine temperature characteristic, miniaturization and weight reduction. The phase shifter using semiconductor materials has two types: transmission-type phase shifters and reflection-type phase shifters. The transmission-type phase shifters are divided again into an open/closed type and a loaded type. The reflection-type phase shifters are divided again into a circulator coupled type and a hybrid coupled type.

Fig. 1 is a graph showing typical phase shifting characteristics between two standard transmission lines according to frequency. Generally, a phase shifter with a simple structure which uses the difference in the

electrical lengths of the transmission lines shows a phase deviation of $\pm\varepsilon_{\Delta\phi}$, which is described in Fig. 1, due to the difference in the frequency-based phase characteristics within a specified band. The phase deviation is caused by the phase dispersion of the transmission lines and it is a major factor for restricting the operational bandwidth of the phase shifter.

In order to reduce the phase deviation within an operational frequency band, many kinds of networks have been studied and reported in many literatures. However, the networks have several drawbacks originated from their own characteristics and the drawbacks work as restrictions on them. Thus, the networks have been used limitedly.

The characteristics and problems of the conventional phase shifters are described herein.

First, a phase shifter having the specific network which uses $\lambda/8$ open and short stubs is proposed in an article by R. B. Wilds entitled "Try $\lambda/8$ stubs for fast fixed phase shifts" in *Microwaves*, pp. 67-68, Vol. 18, December, 1979, which is incorporated herein by reference. The phase-delayed path of the phase shifter uses a standard transmission line having impedance Z_0, and the other path with a leading phase has parallel $\lambda/8$ (45°) open and short stubs in the center of a transmission line having a phase length of 180° ($\lambda/2$). The phase shifter can shift phases optionally in the range of 15° to 135° over octave band.

However, the phase shifter has a shortcoming that the phase shifting range is limited to 15° to 135°, as it is designed to be. Also, since the network of the path with a leading phase has a low impedance characteristic, it is not appropriate for a circuit with a dual-stub structurally.

Another conventional technology, a broadband 180° phase shifter is proposed in an article by Boire, et al. entitled "A 4.5 to 18 GHz Phase shifter" in *IEEE MTT Int. Microwave Symp. Digest*, pp. 601-604, 1985, which is incorporated herein by reference. The phase shifter has a structure in which phase characteristics are shown independently from frequency within the operational band. The phase shifter has a structure of a switched network having two paths. Each path has a coupled transmission line portion and a π hybrid-type network portion. The phase difference between the two paths is relative phase difference, which is 180°.

However, the phase shift of this phase shifter is fixed to 180° and it requires an additional input/output match circuit. The use of the input/output match circuit reduces the operational bandwidth. In addition, it has a drawback in manufacturing that it cannot be realized in a Hybrid Microwave Integrated Circuit (HMIC) technology, which is relatively simple, but formed in a Monolithic Microwave Integrated Circuit (MMIC) technology.

The drawback in manufacturing the broadband 180° phase

shifter is also found in the manufacturing of a Schiffman phase shifter proposed in an article by B. M. Schiffman entitled "A new class of broad-band microwave 90-degree phase shifters" in *IRE Trans. Microwave Theory Tech.*, pp. 232-237, April 1958, which is incorporated herein by reference, and in an article by J.L.R. Quirarte and J.P. Starski entitled "Novel Schiffman phase shifters" in *IEEE Trans. Microwave Theory Tech.*, Vol.MTT-41, PP. 9-14, January 1993, which is incorporated herein by reference. The Schiffman phase shifter can hardly be realized in a thick film technology. The Schiffman phase shifter has a shortcoming in broadband design that bandwidth is decreased as coupling between transmission lines is weaker.

In conclusion, the phase shifters of the prior structures has a problem that their electrical characteristics are restricted due to the shortcomings in manufacturing and designing and the development cost, such as production cost, is expensive.

【Technical Objects of the Invention】

It is, therefore, an object of the present invention, which is devised to resolve the above-mentioned problems, to provide a broadband phase shifter having a new structure of a transmission-type switched network which includes a coupled line, main transmission lines and parallel λ/8 open and short stubs formed on both ends of the main

transmission lines in order to obtain broadband phase characteristics that the phase difference between two networks is uniform.

【Detailed Description of the Invention】

In accordance with an aspect of the present invention, there is provided a broadband phase shifter, including: a first path circuit network including a reference standard transmission line whose input/output characteristic impedance is Z_0 and electrical length is θ_1; a second path circuit network having two symmetrical main transmission lines connected to each other by a coupled line in the center and parallel open and short stubs connected to both ends of the two symmetrical main transmission lines, the main transmission lines having characteristic impedance Z_m and an electrical length θ_m and the parallel open and short stubs having characteristic impedance Z_s and an electrical length θ_s; and a switching means for selecting only one path among the first path circuit network and the second path circuit network.

The objects, features and advantages of the present invention will become apparent from the following description of the preferred embodiments given in conjunction with the accompanying drawings. Hereinafter, the preferred embodiments of the present invention will be described with reference to the accompanying drawings.

Fig. 2 is a schematic diagram describing a network of a broadband phase shifter in accordance with the present invention.

As shown in Fig. 2, the phase shifter circuit network suggested in the present invention can be realized into two structures: a first embodiment where the network has a single coupled line; and a second embodiment where the network has double parallel coupled lines. The network of the broadband phase shifter of the present invention has two paths, i.e., a path 1 and a path 2, and only one path is selected among the two through mutual toggle switching between a pair of diodes D1 and D2 and the other pair of diodes D3 and D4.

First, the network of the broadband phase shifter in Fig. 2(a) is described. Referring to Fig. 2(a), the phase shifter circuit network of the present invention includes a first path circuit network, a second path circuit network, and a switching unit for selecting only one path among the first and second path circuit networks through toggle switching between a pair of a first diode D1 and a second diode D2 and the other pair of a third diode D3 and a fourth diode D4.

The first path circuit network, which is a phase-delaying network, is formed of standard transmission lines (MTL), which can control its electrical length according to a desired phase shift and control input/output

characteristic impedance Z_0 according to the characteristics of a broadband phase shifter to be designed. The electrical length θ_1 of the standard transmission lines has a value obtained by adding a basic phase shift designed at the center frequency f_0, i.e., 180° ($\lambda/2$), to an additional electrical length for obtaining a desired phase shift. The additional electrical length of the standard transmission line shows typical characteristics of in-band phase deviation $\pm\varepsilon_{\Delta\phi}$ (refer to Fig. 1). That is, the phase of the additional electrical length of the standard transmission line is delayed in a frequency band lower than the center frequency, and the phase goes ahead in a frequency band higher than the center frequency.

The second path circuit network includes two symmetrical main transmission lines TL1 and TL2 and a coupled line CL1 in the center. The two symmetrical main transmission lines TL1 and TL2 have characteristic impedance Z_m and an electrical length θ_m. The coupled line CL1 has arbitrary coupling characteristics.

The second path circuit network also includes open and short stubs OSL1, OSL2, SSL1 and SSL2 connected in parallel at both ends of the network. The open and short stubs OSL1, OSL2, SSL1 and SSL2 have characteristic impedance Z_s and an electrical length of $\lambda/8$ (45°).

The second path circuit network comes to have a stronger dispersive phase characteristic than the first

path circuit network by connecting the open and short stubs OSL1, OSL2, SSL1 and SSL2 and by the coupled line CL1. The frequency-based phase slope of the second path circuit network is obtained by controlling the electrical length θ_m (from 0° to 90°) of the main transmission lines TL1 and TL2, the characteristic impedance Z_m of the main transmission lines TL1 and TL2, the characteristic impedance Z_s of the parallel stubs OSL1, OSL2, SSL1 and SSL2, and coupling characteristics R of the coupled line CL1 in accordance with the desired phase shift.

The present invention uses an even mode and odd mode analysis and the superposition principle, which considers structural symmetry based on an ideal lossless transmission line theory, to analyze the structure of the phase shifter proposed in the present invention.

Fig. 3 is an equivalent circuit showing a first path circuit network of the phase shifter circuit network of Fig. 2(a). The input impedances for the even mode and odd mode illustrated in Fig. 3 are expressed as Equations 1 and 2 below.

$$Z_{in,e1} = -jZ_0 \cot(\theta_1/2) \quad \text{Eq. 1}$$

$$Z_{in,o1} = jZ_0 \tan(\theta_1/2) \quad \text{Eq. 2}$$

where Z_0 is input/output impedance.

Also, even and odd mode return coefficients are given as the following Equations 3 and 4 in an input terminal 1.

$$\Gamma_{e,1} = \frac{Z_{in,e1} - Z_0}{Z_{in,e1} + Z_0} = \frac{-1 - j\cot(\theta_1/2)}{1 - j\cot(\theta_1/2)} \qquad \text{Eq. 3}$$

$$\Gamma_{o,1} = \frac{Z_{in,o1} - Z_0}{Z_{in,o1} + Z_0} = \frac{-1 - j\tan(\theta_1/2)}{1 - j\tan(\theta_1/2)} \qquad \text{Eq. 4}$$

Therefore, when the Principle of Superposition is applied to the even and odd mode return coefficients obtained in the first path circuit network and then scattering parameters $S_{i,j}$ (i,j=1,2) for the first path circuit network is induced, the following Equations 5 and 6 are acquired.

$$S_{11} = S_{22} = \frac{1}{2}(\Gamma_{e,1} + \Gamma_{o,1}) = 0 \qquad \text{Eq. 5}$$

$$S_{21} = S_{12} = \frac{1}{2}(\Gamma_{e,1} - \Gamma_{o,1}) = (\cos\theta_1 - j\sin\theta_1) \qquad \text{Eq. 6}$$

Fig. 4 is an equivalent circuit for a second path circuit network of the phase shifter circuit network of Fig. 2(a). The input admittances for even and odd mode equivalent circuits illustrated in Fig. 4 are expressed as the following Equations 7 and 8.

$$Y_{in,e2} = j\left\{\frac{Y_m(Y_{me}\tan\theta_c + Y_m\tan\theta_m)}{Y_m - Y_{me}\tan\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s\right\} \qquad \text{Eq. 7}$$

$$Y_{in,o2} = j\left\{\frac{Y_m(-Y_{mo}\cot\theta_c + Y_m\tan\theta_m)}{Y_m + Y_{mo}\cot\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s\right\} \qquad \text{Eq. 8}$$

The Equations 7 and 8 is based on an equation of $\tan\theta_s - \cot\theta_s = -2\cot\theta_s$, and line characteristic admittance are $Y_m = 1/Z_m$, $Y_{me} = 1/Z_{me}$, $Y_{mo} = 1/Z_{mo}$, and $Y_s = 1/Z_s$.

Also, even and odd mode return coefficients for an input terminal 3 are given as the following Equations 9 and 10.

$$\Gamma_{e,2} = \frac{Y_0 - Y_{in,e2}}{Y_0 + Y_{in,e2}} = \frac{Y_0 - j\left\{\frac{Y_m(Y_{me}\tan\theta_c + Y_m\tan\theta_m)}{Y_m - Y_{me}\tan\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s\right\}}{Y_0 + j\left\{\frac{Y_m(Y_{me}\tan\theta_c + Y_m\tan\theta_m)}{Y_m - Y_{me}\tan\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s\right\}} \qquad \text{Eq. 9}$$

$$\Gamma_{o,2} = \frac{Y_0 - Y_{in,o2}}{Y_0 + Y_{in,o2}} = \frac{Y_0 - j\left\{\frac{Y_m(-Y_{me}\cot\theta_c + Y_m\tan\theta_m)}{Y_m + Y_{mo}\cot\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s\right\}}{Y_0 + j\left\{\frac{Y_m(-Y_{mo}\cot\theta_c + Y_m\tan\theta_m)}{Y_m + Y_{me}\cot\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s\right\}} \qquad \text{Eq. 10}$$

where Y_0 denotes an input/output admittance.

Therefore, when the Principle of Superposition is applied to the even and odd mode return coefficients obtained in the second path circuit network and then scattering parameters $S_{i,j}$ (i,j=3,4) for the second path

circuit network is induced, the following Equations 11 and 12 are acquired.

$$S_{33} = S_{44} = \frac{1}{2}(\Gamma_{e,2} + \Gamma_{o,2}) = \frac{1}{2}\left(\frac{Y_0 - jT_e(f)}{Y_0 + jT_e(f)} + \frac{Y_0 + jT_o(f)}{Y_0 - jT_o(f)}\right)$$

Eq. 11

$$S_{43} = S_{34} = \frac{1}{2}(\Gamma_{e,2} - \Gamma_{o,2}) = \frac{1}{2}\left(\frac{Y_0 - jT_e(f)}{Y_0 + jT_e(f)} - \frac{Y_0 + jT_o(f)}{Y_0 - jT_o(f)}\right)$$

Eq. 12

where $T_e(f)$ and $T_o(f)$ are as the following Equations 13 and 14, and θ_m, θ_c, and θ_s are all frequency functions.

$$T_e(f) = \frac{Y_m(Y_{me}\tan\theta_c + Y_m\tan\theta_m)}{Y_m - Y_{me}\tan\theta_c\tan\theta_m} - 2Y_s\cot 2\theta_s$$

Eq. 13

$$T_o(f) = \frac{Y_m(Y_{mo}\cot\theta_c - Y_m\tan\theta_m)}{Y_m + Y_{mo}\cot\theta_c\tan\theta_m} + 2Y_s\cot 2\theta_s$$

Eq. 14

Meanwhile, the second path circuit network of Fig. 2(a) has design parameters Z_m, Z_{me}, Z_{mo}, Z_s, θ_m, θ_c and θ_s. Among the design parameters, the θ_s value is 45° at the center frequency independently. To satisfy the electrical

characteristics of the network at the center frequency, the Z_{me}, Z_{mo}, and θ_c values should satisfy the relations expressed in Equations 15, 16, and 17.

$$Z_{me} = \sqrt{R} Z_m \qquad \text{Eq. 15}$$

$$Z_{mo} = Z_m / \sqrt{R} \qquad \text{Eq. 16}$$

$$\theta_c = \tan^{-1}\left(\sqrt{R\left\{ \frac{1-\cos(180° - 2\theta_m)}{1+\cos(180° - 2\theta_m)} \right\}} \right) \qquad \text{Eq. 17}$$

where $R = Z_{me} / Z_{mo}$, and the entire electrical length of the main transmission line and the coupled line is 180° at the center frequency.

From the condition for the electrical length, Equation 17 can be derived as above, and the characteristic impedance Z_m of the main transmission line can be changed while the input/output match is maintained.

The other parameters Z_m, Z_s and θ_m of the second path circuit network and the parameter R that determines the coupling characteristics of a new coupled line decide phase dispersive characteristics (or phase slope) of the network. They can be determined arbitrarily by considering input/output match fixed at the desired phase shift and design conditions for phase deviations. Each parameter

should be determined to form the circuit network easily. Graphs for the relationships for the design parameters Z_m, Z_s, θ_m and R will be described in detail later.

The relative transmission phase shift quantity of the phase shifter of Fig. 2(a) can be expressed as the following equation 18 based on the equations 6 and 7.

$$\Delta\phi_\Gamma(f) = ang(S_{21}) - ang(S_{43}) = -\theta_1(f) + \pi - \tan^{-1}\left(\frac{Y_O^{\,2} + T_e T_O}{T_e - T_O}\right)$$ Eq. 18

where $\theta_1(f) = [\pi + \Delta\phi_\Gamma(f_o)]\bar{f}, \bar{f} = f / f_o$.

The input/output impedance of the first path circuit network of the broadband phase shifter of Fig. 2(a) is already matched, and the size is always 1 in connection with delivery characteristics and only the phase is delayed by θ_1.

Meanwhile, since the second path circuit network has values $T_e(f_0) = \infty$ and $T_o(f_0) = 0$ at the center frequency, $S_{33} = S_{44} = 0$ and $S_{34} = S_{43} = -1$ at the center frequency. In the frequencies out of the center frequency, the second path circuit network has finite values $T_e(f) = \alpha$ and $T_o(f) = \beta$. Herein, α and β are real numbers.

Also, a phase error can be expressed as the following equation 19.

$$\varepsilon_{\Delta\phi}(f) = \pm\left|\Delta\phi_\Gamma(f) - \Delta\phi_\Gamma(f_o)\right|$$ Eq. 19

where $\Delta\phi_{\Gamma}(f_o)$ is a phase shift quantity at the center frequency.

Meanwhile, it is obvious to those skilled in the art that what can be applied to the other embodiments in what has been presented in the embodiment of Fig. 2(a) can be applied without any specific mention in the other embodiments. Therefore, it is possible to theoretically analyze the circuit structure of Fig. 2(b), which is another embodiment of present invention, in the same method as one used in the circuit network of Fig. 2(a).

As described above, the phase shifter structure of Fig. 2 can be applied to the design of general phase shifter having a predetermined phase shift. Particularly, the reference circuit network of the second path is suitable for the design of a broadband phase shifter having a relatively large phase shift such as 180° bits, because open and short parallel stubs OSL1, OSL2, SSL1, and SSL2 can be combined with coupled lines CL1 and CL2 and provide stronger phase scattering characteristics doubly.

Meanwhile, a 180° phase shifter is the most significant unit bit phase shifter that most affects the electric characteristics, i.e., bandwidth characteristics, when a digital phase shifter is designed. The phase scattering characteristics by the open and short parallel

stubs OSL1, OSL2, SSL1 and SSL2 in the reference circuit network are far superior to the phase scattering characteristics by the coupled lines CL1 and CL2. Hereafter, a process of designing a 180° phase shifter by using the phase shifter structure of the present invention will be described in detail.

In order to optimize the input/output impedance matching and phase characteristics based on frequency response, the relationship among the design parameters Z_m, Z_s, θ_m and R should be selected optimally through computer simulations based on the equations 11, 15, 17 and 19. The impedance ratio (R) of the coupled lines CL1 and CL2 that can be fabricated in the HMIC technique using a substrate of a low dielectric rate is not more than 1.7 in most cases. Therefore, a 180° phase shifter that can be easily realized in the HMIC technique practically should have circuit parameters satisfying design conditions that R=1.7, VSWR = 1.15:1 (which corresponds a return loss characteristic of 23.12dB), and the maximum phase error $\leq \pm 2$ from the above design standpoint.

The circuit design parameters Z_m and Z_s are optimal values according to the variation of the θ_m value through computer simulations based on the equations 11, 15 to 17 and 19, which is shown in Fig. 5.

Fig. 5 is a graph showing optimal Z_m and Z_s values by θ_m variations. In Fig. 5, the relationship between

characteristic impedance Z_m of the main transmission lines TL1 and TL2 and the characteristic impedance Z_s of the stubs OSL1, OSL2, SSL1 and SSL2, which satisfies the design conditions of given input/output matching and the maximum phase error simultaneously, is that the impedance Z_m increases non-linearly while the impedance Z_s decreases non-linearly, as the θ_m value becomes higher. Particularly, the impedances Z_m and Z_s have the same value when the θ_m value is about 34.3°. Also, the input/output matching and phase bandwidths have a relationship as shown in the graph of Fig. 6 according to the θ_m variations under the same design conditions.

When the Z_m and Z_s values of Fig. 5 that satisfies the design conditions of the given input/output matching and the maximum phase error simultaneously are applied, the input/output VSWR bandwidth is decreased smoothly, as the θ_m increases, and it maintains almost the same value at the θ_m value of more than 40°. On the contrary, the phase response bandwidth decreases relatively sharply until the θ_m value becomes about 30° and then it increases again smoothly. When the θ_m value is 90°, the θ_c value becomes 0°, thus removing phase scattering characteristics of the coupled lines CL1 and CL2 in the second path circuit network. When an R value is 1.7, it can be known from the graph of Fig. 6 that the electric length θ_m of the main transmission lines should be not more than 23.3° in order

to acquire the effect of increased input/output VSWR bandwidth and phase response bandwidth due to the phase scattering characteristics of the coupled lines. All the maximum input/output VSWR bandwidth and phase response bandwidth have a θ_m value of 0° and they have values of 50.6% and 65.2%, respectively.

Hereinafter, circuit design parameters based on R variations, which is an impedance ratio between the coupled lines CL1 and CL2 will be described in detail when the main transmission lines TL1 and TL2 have an electric length θ_m of 0°. The circuit design parameters Z_m and Z_s which satisfy a design condition I of input/output VSWR=1.15:1 and the maximum phase error ≤ ±2; and a design condition I of input/output VSWR=1.25:1 (which corresponds to a return loss characteristic of 19.8dB and the maximum phase error ≤ ±5 are given optimally according to the R variations in the graph of Fig. 7.

As illustrated in Fig. 7, the relationship between characteristic impedance Z_m of the main transmission lines TL1 and TL2 and the characteristic impedance Z_s of the stubs OSL1, OSL2, SSL1 and SSL2is that the impedance Z_m decreases non-linearly while the impedance Z_s increases non-linearly, as the R value becomes higher. Also, the input/output matching and phase bandwidths based on the R variations under the same conditions are given as shown in the graph of Fig. 8. The graph of Fig. 8 shows that the

bandwidths are increased remarkably and generally when the design condition is eased from the design condition I to the design condition II.

The 180° phase shifter designed according to the present invention has a phase bandwidth characteristic of 106.3% when the R value is about 2.2 under the design condition I and it has a phase bandwidth characteristic of up to 121% when the R value is about 1.6 under the design condition II.

Meanwhile, it can be known from the drawing that the input/output impedance matching bandwidth increases slowly according to the increasing R value. As seen in the graph of Fig. 7, the impedance Z_m slowly converges into 50Ω as the R value increases and, on the contrary, the impedance Z_s increases sharply relatively and the open and short stubs fail to perform properly in the circuit network of the path.

Figs. 9 and 10 are graphs presenting normalized frequency response characteristics of input/output return loss and phase errors by R variations under design conditions I and II. Generally, the parallel stubs OSL 1, OSL2, SSL1 and SSL2 connected to the main transmission lines TSL1 and TL2 of a circuit show band stop characteristics. Thus, as shown in Fig. 9, the severe impedance degradation characteristics in the bands out of an operation frequency band are originated from the

frequency limitation by the stubs. Fig. 9 shows that the input/output impedance bandwidth is increased as the R value is increased. This is because the impedance of stubs OSL1, OSL2, SSL1 and SSL2 are increased gradually while the impedances of the main transmission lines TL1 and TL2 converge into around 50 Ω. On the other hand, the phase bandwidth illustrated in the graph of Fig. 10 has a characteristic that the phase bandwidth increases and than decreases according to the R variations. In order to prove a theory and design on a structure of the 180° broadband phase shifter suggested under electric performance conditions of input/output VSWR = 1.15:1 and the maximum phase error ≤ ±2, four kinds of phase shifters that operate at the center frequency of 3GHz are fabricated by utilizing TLY-5A Tefron substrates produced by the Taconic Company. The TLY-5A Tefron substrates have a dielectric rate of 2.17, substrate thickness of 20 mils, copper film thickness of 0.5oz, and tangent loss of 0.0009 (@10GHz). The impedance ratio R of feasible coupled lines is determined to be 1.7 in consideration of allowable error of the HMIC technology, and the lengths θ_m of main transmission lines TL1 and TL2 are 0° (a first phase shifter), 10° (a second phase shifter), and 90° (a third phase shifter). When the θ_m is 90°, the coupled lines CL1 and CL2 are not used. Also, to compare their phase characteristics with those of conventional Standard Shiffman phase shifters, four

Standard Shiffman phase shifters with R=1.7 are designed and fabricated. The design parameters for the phase shifters are summarized and presented in Table 1 below by using the design graph of Fig. 5 acquired from simulations based on Equations 11, 15 to 17, and 19.

Table 1

Design parameter values of a reference circuit network in a 180° phase shifter suggested in the present invention.

Item		θ_m			Standard Schiffman
		0°	10°	90°	
Main transmission line & Stubs	Z_m	63.8Ω	65.3Ω	80.5Ω	50.0Ω
	Z_s	84.1Ω	80.6Ω	63.7Ω	-
	θ_s	45.0°	45.0°	45.0°	-
Coupled Line (R=1.7)	Z_{me}	83.2Ω	85.1Ω	-	65.2Ω
	Z_{mo}	48.9Ω	50.1Ω	-	38.3Ω
	θ_c	90.0°	82.3°	-	90.0°
Bandwidth	Input/output Match	50.4%	48.7%	46.1%	∞(Match)
	Phase	65.4%	56.3%	50.6%	3.2%

Referring to Table 1, the standard Schiffman phase

shifter shows superior input/output match bandwidth, compared to the phase shifters of other structures proposed in the present invention. However, it has remarkably poor phase bandwidth. When the R value is given 1.7 for all the phase shifters and their main transmission line impedances are compared, that of the standard Schiffman phase shifter is the smallest. This means that the odd mode impedance Z_{mo} of the coupled lines CL1 and CL2 is relatively small and it is difficult to form the coupled lines CL1 and CL2.

Fig. 11 presents photographs of a 180° phase shifter fabricated independently.

Figs. 12 to 15 are graphs comparing simulated electric performances of the phase shifters of Fig. 11 simulated by using a commercial electromagnetic (EM) simulator with electric performance measured by using an HP 8510C vector network analyzer. The experimental results shown in the graphs of Fig. 15 are obtained with an input/output SMA (Subminiature A) connector, and the results show characteristics of the connector and impedance change of the coupled lines originated from under etching of a printed circuit board (PCB). The measurement results have showed that the input/output matching and phase characteristics are a little different from the EM simulated results or ideal results due to external restrictions related to the connector or the PCB. However, the error in the performance can become closer to the EM

simulated results or ideal results by compensating the connector characteristics and reducing the PCB under etching. Generally, the electric characteristics of the measured results are accorded with those of the simulated results. The bandwidth in consideration of the input/output return loss 14dB, or VSWR = 1.5:1, and the phase bandwidth characteristics in consideration of the maximum phase error ±5 are summarized and presented in Table 2 below.

Table 2. Measured bandwidths of the 180° phase shifter suggested in the present invention

Item	θ_m=0°	θ_m=10°	θ_m=90°	Standard Schiffman
14dB Return Loss Bandwidth	66.8%	61.3%	57.1%	∞(Match*)
±5° Phase Bandwidth	94.8%	62.5%	55.8%	8.7%

(*) 12 dB return loss is considered.

The measured data of Table 2 show that the input/output match and phase bandwidth characteristics are most excellent at θ_m =0°. Since the conditions for measuring the bandwidth characteristics are different, the measured bandwidth characteristics of Table 2 cannot be compared precisely with the ideal bandwidth characteristics

of Table 1. However, it is clear that the 180° phase shifter with a structure proposed in the present invention can obtain broadband characteristics using Hybrid Microwave Integrated Circuit (HMIC) or Monolithic Microwave Integrated Circuit (MMIC) designing technology, compared to phase shifters with conventional structures.

While the present invention has been described with respect to certain preferred embodiments, it will be apparent to those skilled in the technology that various changes and modifications may be made without departing from the scope of the invention as defined in the following claims.

【Effects of the Invention】

The phase shifter of the present invention can obtain broadband characteristics by correcting the phase deviation for a desired phase shift with the ratio of a standard network between the characteristic impedance of the double parallel $\lambda/8$ (45°) open and short stubs, the characteristic impedance of the main transmission lines, and the coupling impedance of the coupled line. Since the standard network can provide stronger phase dispersive characteristic, a broadband phase shifter having a relatively large phase shift, such as 180° can be fabricated easily. In addition, the use of coupled line in the present invention helps miniaturize the circuit. Therefore, the technology of the

present invention overcomes the shortcoming in manufacturing conventional phase shifters and fabricates a phase shifter both in the HMIC and MMIC technology.

【Claims】

【Claim 1】

A broadband phase shifter, comprising:

a first path circuit network including a reference standard transmission line whose input/output characteristic impedance is Z_0 and electrical length is θ_1;

a second path circuit network having two symmetrical main transmission lines connected to each other by a coupled line in the center and parallel open and short stubs connected to both ends of the two symmetrical main transmission lines, the main transmission lines having characteristic impedance Z_m and an electrical length θ_m and the parallel open and short stubs having characteristic impedance Z_s and an electrical length θ_s; and

a switching means for selecting only one path among the first path network and the second path network.

【Claim 2】

The broadband phase shifter as recited in claim 1, wherein the coupled line is of a single structure.

【Claim 3】

The broadband phase shifter as recited in claim 1, wherein the coupled line is of a double parallel structure.

【Claim 4】

The broadband phase shifter as recited in any one of claims 1 to3, wherein the reference standard transmission line of the first path circuit network has an input/output characteristic impedance Z_0 and an electrical length θ_1, the Z_0 and θ_1 values being controllable according to a desired phase shift.

【Claim 5】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the electrical length θ_1 of the reference standard transmission line of the first path circuit network has a value obtained by adding an additional electrical length to a basic phase shift designed at the center frequency f_0 of an operating frequency band to acquire the desired phase shift.

【Claim 6】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein equivalent impedances Z_{me} and Z_{mo} for an even mode and an odd mode, the electrical length θ_c, and the coupling characteristics R of the coupled line of the second path circuit network have a relationship expressed by:

$$Z_{me} = \sqrt{R} Z_m$$
$$Z_{mo} = Z_m / \sqrt{R}$$

$$\theta_c = \tan^{-1}\left(\sqrt{R\left\{\frac{1-\cos(180^\circ - 2\theta_m)}{1+\cos(180^\circ - 2\theta_m)}\right\}}\right)$$

where $R = Z_{me} / Z_{mo}$.

【Claim 7】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the electrical length of the main transmission lines and the coupled line of the second path network is 180° at the center frequency.

【Claim 8】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the electrical length of the parallel open and short stubs of the second path circuit network is 45° at the center frequency.

【Claim 9】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the phase slope based on the frequency of the second path circuit network is determined by controlling the electrical length θ_m of the main transmission lines, characteristic impedance Z_m of the main transmission lines, characteristic impedance Z_s of the parallel stubs, and the coupling characteristic R of the coupled line.

【Claim 10】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the switching means selects only one path among the first path circuit network and the second path circuit network through toggle switching between a pair of a first diode and a second diode connected to the first path circuit network and a pair of a third diode and a fourth diode connected to the second path circuit network.

【Claim 11】

The broadband phase shifter as recited in claim 5, wherein the basic phase shift designed at the center frequency f_0 of the operating frequency band is 180°.

【Claim 12】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein scattering parameters of the first path circuit network are expressed as:

$$S_{11} = S_{22} = \frac{1}{2}(\Gamma_{e,1} + \Gamma_{o,1}) = 0$$

$$S_{21} = S_{12} = \frac{1}{2}(\Gamma_{e,1} - \Gamma_{o,1}) = (\cos\theta_1 - j\sin\theta_1)$$

【Claim 13】

The broadband phase shifter as recited in any one of

claims 1 to 3, wherein scattering parameters of the second path circuit network are expressed as:

$$S_{33} = S_{44} = \frac{1}{2}(\Gamma_{e,2} + \Gamma_{o,2}) = \frac{1}{2}\left(\frac{Y_0 - jT_e(f)}{Y_0 + jT_e(f)} + \frac{Y_0 + jT_o(f)}{Y_0 - jT_o(f)}\right)$$

$$S_{43} = S_{34} = \frac{1}{2}(\Gamma_{e,2} - \Gamma_{o,2}) = \frac{1}{2}\left(\frac{Y_0 - jT_e(f)}{Y_0 + jT_e(f)} - \frac{Y_0 + jT_o(f)}{Y_0 - jT_o(f)}\right)$$

【Claim 14】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein relative phase shift quantities of the phase shifter are expressed as:

$$\Delta\phi_\Gamma(f) = ang(S_{21}) - ang(S_{43}) = -\theta_1(f) + \pi - \tan^{-1}\left(\frac{Y_O{}^2 + T_e T_O}{T_e - T_O}\right)$$

where $\theta_1(f) = [\pi + \Delta\phi_\Gamma(f_o)]\bar{f}, \bar{f} = f / f_o$.

【Claim 15】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the characteristic impedance of the main transmission lines of the second path circuit network is increased non-linearly as the electric length of the main transmission line of the second path circuit network is increased, and

the characteristic impedance of the open and short stubs of the second path circuit network is decreased non-linearly as the electric length of the main transmission

line of the second path circuit network is increased.

【Claim 16】

The broadband phase shifter as recited in any one of claims 1 to 3, wherein the characteristic impedance of the main transmission lines of the second path circuit network is decreased non-linearly as the coupling characteristic of the coupled line of the second path network is increased, and

the characteristic impedance of the open and short stubs of the second path circuit network is increased non-linearly as the coupling characteristic of the coupled line of the second path circuit network is increased.